Measurements of gluon-gluon fusion and vector-boson fusion Higgs boson production cross-sections in the $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ decay channel in pp collisions at $\sqrt{s}=13$ TeV with the ATLAS detector

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ABSTRACT

Higgs boson production cross-sections in proton–proton collisions are measured in the $H \to WW^* \to e\nu\mu\nu$ decay channel. The proton–proton collision data were produced at the Large Hadron Collider at a centre-of-mass energy of 13 TeV and recorded by the ATLAS detector in 2015 and 2016, corresponding to an integrated luminosity of 36.1 fb^{-1}. The product of the $H \to WW^*$ branching fraction times the gluon–gluon fusion and vector-boson fusion cross-sections are measured to be $11.4^{+1.2}_{-1.1}(\text{stat.})^{+1.8}_{-1.7}(\text{syst.})$ pb and $0.50^{+0.24}_{-0.22}(\text{stat.}) \pm 0.17(\text{syst.})$ pb, respectively, in agreement with Standard Model predictions.

1. Introduction

This Letter presents a measurement of the inclusive Higgs boson production cross-sections via gluon–gluon fusion (ggF) and vector-boson fusion (VBF) through the decay $H \to WW^* \to e\nu\mu\nu$ using 36.1 fb^{-1} of proton–proton collisions at a centre-of-mass energy of 13 TeV recorded by the ATLAS detector. Higgs boson couplings have been studied in this channel with Run-1 data by the ATLAS [1] and CMS [2] experiments and recently with Run-2 data by the CMS experiment [3]. The $H \to WW^*$ decay channel has the second-largest branching fraction and allowed the most precise Higgs boson cross-section measurements in Run-1 [4]. The measured cross-section of the ggF production process probes the Higgs boson couplings to gluons and heavy quarks, while the VBF process directly probes the couplings to W and Z bosons. The leading-order diagrams for the ggF and VBF production processes are depicted in Fig. 1.

2. ATLAS detector

ATLAS is a particle detector designed to achieve a nearly full coverage in solid angle[1] [5,6]. It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer incorporating three large superconducting air-core toroidal magnets. The inner tracking detector (ID) is located in a 2 T magnetic field and is designed to measure charged-particle trajectories up to a pseudorapidity of $|\eta| = 2.5$. Surrounding the ID are electromagnetic and hadronic calorimeters, which use liquid argon (LAr) and lead absorber for the electromagnetic central and endcap calorimeters ($|\eta| < 3.2$), copper absorber for the hadronic endcap calorimeter ($1.5 < |\eta| < 3.2$), and scintillator-tile active material with steel absorber for the central ($|\eta| < 1.7$) hadronic calorimeter. The solid angle coverage is extended to $|\eta| = 4.9$ with forward copper/LAr and tungsten/LAr calorimeter modules. The muon spectrometer comprises separate trigger chambers within the range $|\eta| < 2.4$ and high-precision tracking chambers within the range $|\eta| < 2.7$, measuring the deflection of muons in a magnetic field generated by the three superconducting toroidal magnets. A two-level trigger system is used to select events [7].

3. Signal and background Monte Carlo predictions

Higgs boson production via ggF was simulated at next-to-next-to-leading-order (NNLO) accuracy in QCD using the POWHEG-BOX v2 NNLOPS program [8], with the PDF4LHC15 NNLO set of parton distribution functions (PDF) [9]. The simulation achieves NNLO accuracy for arbitrary inclusive $gg \to H$ observables by reweighting the Higgs boson rapidity spectrum in Hj-MiNLO [10] to that of HNNLO [11]. The transverse momentum spectrum of the Higgs bo-

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[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. The distance in (η, ϕ) coordinates, $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$, is also used to define cone sizes. Transverse momentum and energy are defined as $p_T = p\sin\theta$ and $E_T = E\sin\theta$, respectively.

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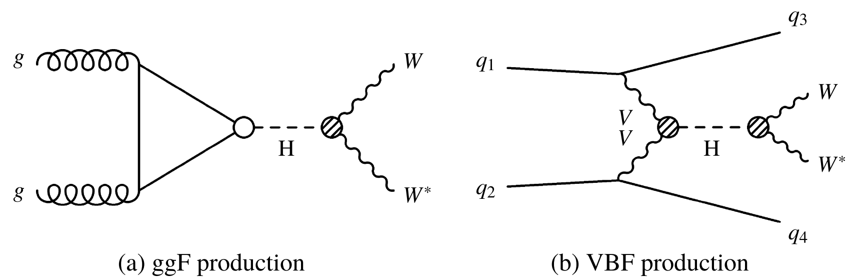


Fig. 1. Diagrams for the leading production modes (ggF and VBF), where the VVH and qqH coupling vertices are marked with shaded and empty circles, respectively. The V represents a W or Z vector boson.

Table 1
Overview of simulation tools used to generate signal and background processes, and to model the UEPS. The PDF sets are also summarised. Alternative event generators and configurations used to estimate systematic uncertainties are shown in parentheses.

Process	Matrix element (alternative)	PDF set	UEPS model (alternative model)	Prediction order for total cross-section
ggF H	Powheg-Box v2 NNLOPS [8,10,16] (MG5_aMC@NLO [47,48])	PDF4LHC15 NNLO [9]	Pythia 8 [14] (Herwig 7 [49])	N^3LO QCD + NLO EW [24–28]
VBF H	Powheg-Box v2	PDF4LHC15 NLO	Pythia 8 (Herwig 7)	NNLO QCD + NLO EW [24,29–31]
VH	Powheg-Box v2 [50]	PDF4LHC15 NLO	Pythia 8	NNLO QCD + NLO EW [51–53]
$qq \to WW$	Sherpa 2.2.2 [32,33] (Powheg-Box v2, MG5_aMC@NLO)	NNPDF3.0NNLO [34]	Sherpa 2.2.2 [35,36] (Herwig++ [49])	NLO [37]
$gg \to WW$	Sherpa 2.1.1 [37]	CT10 [54]	Sherpa 2.1	NLO [38]
$WZ/V\gamma^*/ZZ$	Sherpa 2.1	CT10	Sherpa 2.1	NLO [37]
$V\gamma$	Sherpa 2.2.2 (MG5_aMC@NLO)	NNPDF3.0NNLO	Sherpa 2.2.2 (CSS variation [35,55])	NLO [37]
$t\bar{t}$	Powheg-Box v2 [56] (Sherpa 2.2.1)	NNPDF3.0NLO	Pythia 8 (Herwig 7)	NNLO + NNLL [57]
Wt	Powheg-Box v1 [58] (MG5_aMC@NLO)	CT10 [54]	Pythia 6.428 [59] (Herwig++)	NLO [58]
Z/γ^*	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	NNLO [60,61]

son obtained with this sample was found to be compatible within uncertainties with the resummed NNLO+NNLL HRes2.3 calculation [12,13]. The parton-level events produced by the Powheg-Box v2 NNLOPS program were passed to Pythia 8 [14] to provide parton showering, hadronisation and the underlying event, using the AZNLO set of data-tuned parameters [15].

Higgs boson production via VBF was simulated at next-to-leading-order (NLO) accuracy in QCD using Powheg-Box v2 [8,10,16,17] with the PDF4LHC15 NLO PDF set [9]. The parton-level events were passed to Pythia 8 [14] with the same parameters as for ggF.

The mass of the Higgs boson was set to 125 GeV, compatible with the experimental measurement [18–20]. The corresponding Standard Model (SM) branching fraction $\mathcal{B}_{H\to WW^*}$ is calculated using HDecay v6.50 [21,22] to be 0.214 [23]. The $H\to WW^*\to \ell\nu\ell\nu$ decay, where $\ell = e$ or μ, always includes the small contribution from $W \to \tau\nu \to \ell\nu\nu\nu$ decays. Other production and decay modes of the Higgs boson are either fixed to SM predictions (VH production and $H\to\tau\tau$ decay) or neglected ($t\bar{t}H$ and $b\bar{b}H$ associated production).

The ggF production cross-section was calculated with next-to-next-to-next-to-leading-order accuracy in QCD and includes NLO electroweak (EW) corrections [24–28]. The NLO QCD and EW calculations are used with approximate NNLO QCD corrections for the VBF production cross-section [24,29–31].

The WW background was generated separately for the $qq \to WW$ and $gg \to WW$ production mechanisms. The $qq \to WW$ production process was generated using Sherpa 2.2.2 [32,33] interfaced with the NNPDF3.0 NNLO PDF set [34] and the Sherpa parton shower, hadronisation and underlying event simulation (UEPS) model [35,36]. The matrix elements were calculated for up to one additional parton at NLO and up to three additional partons at LO precision. The loop-induced $gg \to WW$ process was simulated by Sherpa 2.1.1 with zero or one additional jet [37]. The sample is normalised to the NLO $gg \to WW$ cross-section [38]. Interferences with direct WW production have a negligible impact after event selection cuts have been applied and are, therefore, not considered in this analysis [39].

While NNLO cross-sections are available for diboson production processes [40–42], the Sherpa MEPS@NLO prescription [36] is used in this analysis. This procedure already captures the majority of the NNLO shape corrections.

The MC generators, PDFs, and programmes used for the UEPS are summarised in Table 1. The order of the perturbative prediction for each sample is also reported.

The generated events were passed through a Geant 4 [43] simulation of the ATLAS detector [44] and reconstructed with the same analysis software as used for the data. Additional proton–proton interactions (pile-up) are included in the simulation for all generated events such that the distributions of the average number of interactions per bunch crossing reproduces that observed in the data. The inelastic proton–proton collisions were produced using Pythia 8 with the A2 set of data-tuned parameters [45] and the MSTW2008LO PDF set [46]. Correction factors are applied to account for small differences observed between data and simulation in electrons, muons, and jets identification efficiencies and energy/momentum scales and resolutions.

4. Event selection and categorisations

Events are triggered using single-lepton triggers and a dilepton e–μ trigger. The transverse momentum threshold ranges be-

Table 2
Event selection criteria used to define the signal regions in the $H \to WW^* \to e\nu\mu\nu$ analysis. For the $N_{\mathrm{jet}} \geq 2$ VBF signal region, the input variables used for the boosted decision tree (BDT) training are also reported.

<table>
<tr><th>Category</th><th>$N_{\mathrm{jet},(p_{\mathrm{T}}>30\ \mathrm{GeV})} = 0$ ggF</th><th>$N_{\mathrm{jet},(p_{\mathrm{T}}>30\ \mathrm{GeV})} = 1$ ggF</th><th>$N_{\mathrm{jet},(p_{\mathrm{T}}>30\ \mathrm{GeV})} \geq 2$ VBF</th></tr>
<tr><td rowspan="2">Preselection</td><td colspan="3">Two isolated, different-flavour leptons ($\ell = e, \mu$) with opposite charge
$p_{\mathrm{T}}^{\mathrm{lead}} > 22$ GeV, $p_{\mathrm{T}}^{\mathrm{sublead}} > 15$ GeV
$m_{\ell\ell} > 10$ GeV</td></tr>
<tr><td colspan="2">$p_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV</td><td></td></tr>
<tr><td rowspan="3">Background rejection</td><td colspan="3">$N_{b\text{-jet},(p_{\mathrm{T}}>20\ \mathrm{GeV})} = 0$</td></tr>
<tr><td rowspan="2">$\Delta\phi(\ell\ell, E_{\mathrm{T}}^{\mathrm{miss}}) > \pi/2$
$p_{\mathrm{T}}^{\ell\ell} > 30$ GeV</td><td>$\max\left(m_{\mathrm{T}}^{\ell}\right) > 50$ GeV</td><td></td></tr>
<tr><td colspan="2">$m_{\tau\tau} < m_Z - 25$ GeV</td></tr>
<tr><td>$H \to WW^* \to e\nu\mu\nu$ topology</td><td colspan="2">$m_{\ell\ell} < 55$ GeV
$\Delta\phi_{\ell\ell} < 1.8$</td><td>central jet veto
outside lepton veto</td></tr>
<tr><td>Discriminant variable
BDT input variables</td><td colspan="2">m_{T}</td><td>BDT
m_{jj}, Δy_{jj}, $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, m_{T}, $\sum_\ell C_\ell$, $\sum_{\ell,j} m_{\ell j}$, $p_{\mathrm{T}}^{\mathrm{tot}}$</td></tr>
</table>

tween 24 GeV and 26 GeV for single-electron triggers and between 20 GeV and 26 GeV for single-muon triggers, depending on the run period [7]. The e–μ trigger requires a minimum p_{T} threshold of 17 GeV for electrons and 14 GeV for muons.

Electron candidates are reconstructed from energy clusters in the electromagnetic calorimeter with an associated well-reconstructed track [62,63]. Electrons are required to satisfy $|\eta| < 2.47$, excluding the transition region between the barrel and endcap calorimeters, $1.37 < |\eta| < 1.52$. Muon candidates are selected from tracks reconstructed in the ID matched to tracks reconstructed in the muon spectrometer [64] and are required to satisfy $|\eta| < 2.5$. To reject particles misidentified as leptons, several identification requirements as well as calorimeter and track isolation criteria [64,65] are applied. The electron identification criteria applied provide an efficiency in the range 88–94% depending on electron p_{T} and η. For muons, high efficiency, close to 95%, is observed over the full instrumented η range. The final lepton-selection criteria require two different-flavour opposite-sign leptons, the higher-p_{T} (leading) lepton with $p_{\mathrm{T}} > 22$ GeV and the subleading lepton with $p_{\mathrm{T}} > 15$ GeV. At least one of the leptons must correspond to a lepton that triggered the recording of the event. When the e–μ trigger is solely responsible for the recording of the event, each lepton must be matched to one of the trigger objects. The trigger matching requires the offline p_{T} of the matching object to be higher than the trigger level threshold by at least 1 GeV. Jets are reconstructed using the anti-k_t algorithm [66] with a radius parameter $R = 0.4$. The four-momenta of jets are corrected for the non-compensating response of calorimeter, signal losses due to noise threshold effects, energy lost in non-instrumented regions, and contributions from pile-up [67]. Jets are required to have $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 4.5$. A multivariate selection that reduces contamination from pile-up [68] is applied to jets with $p_{\mathrm{T}} < 60$ GeV and $|\eta| < 2.4$, utilising calorimeter and tracking information to separate hard-scatter jets from pile-up jets. For jets with $p_{\mathrm{T}} < 50$ GeV and $|\eta| > 2.5$, jet shapes and topological jet correlations in pile-up interactions are exploited to reduce contamination. Jets with $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.5$ containing b-hadrons (b-jets) are identified using a multivariate technique having as input the track impact parameters and information from secondary vertices. The adopted working point provides a nominal 3% light-flavour (u-, d-, s-quark and gluon) misidentification rate and a 32% c-jet misidentification rate with an average 85% b-jet tagging efficiency, as estimated from simulated $t\bar{t}$ events [69]. Ambiguities from overlapping reconstructed jet and lepton candidates are resolved as follows. If a reconstructed muon shares an ID track with a reconstructed electron, the electron is removed. Reconstructed jets geometrically overlapping in a cone of radius $\Delta R = 0.2$ with electrons or muons are also removed. Electrons and muons, with transverse momentum p_{T}, are removed if they are within $\Delta R = \min(0.4, 0.04 + 10\ \mathrm{GeV}/p_{\mathrm{T}})$ of the axis of any surviving jet. The missing transverse momentum $\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}$ (with magnitude $E_{\mathrm{T}}^{\mathrm{miss}}$) is defined as the negative vector sum of the p_{T} of all the selected leptons and jets, and including reconstructed tracks not associated with these objects, and consistent with originating from the primary pp collision [70]. A second definition of missing transverse momentum (in this case denoted $p_{\mathrm{T}}^{\mathrm{miss}}$) uses the tracks associated with the jets instead of the calorimeter-measured jets. It was found during the optimisation that $p_{\mathrm{T}}^{\mathrm{miss}}$ performs better in terms of background rejection [70].

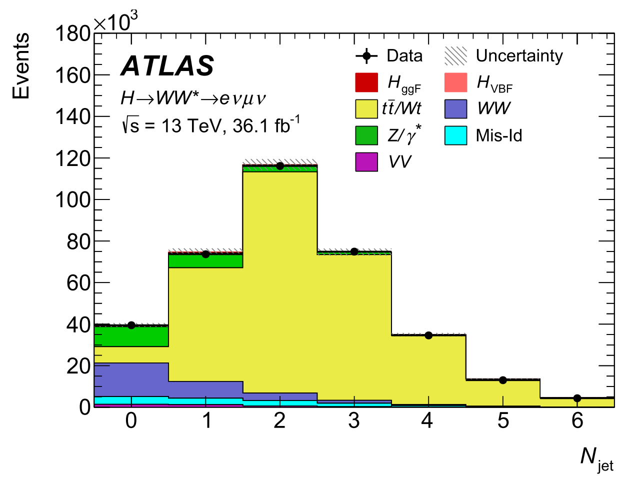
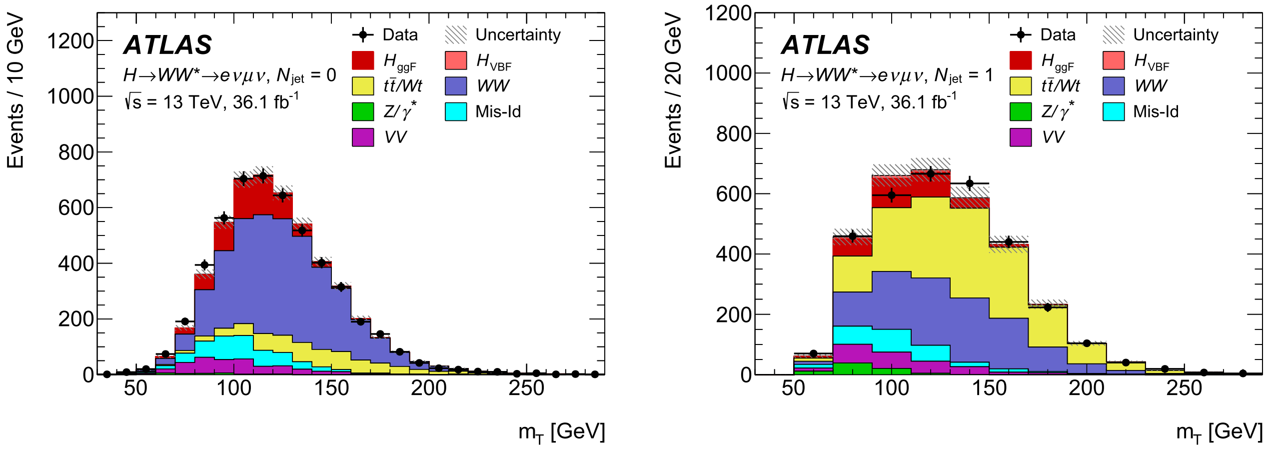


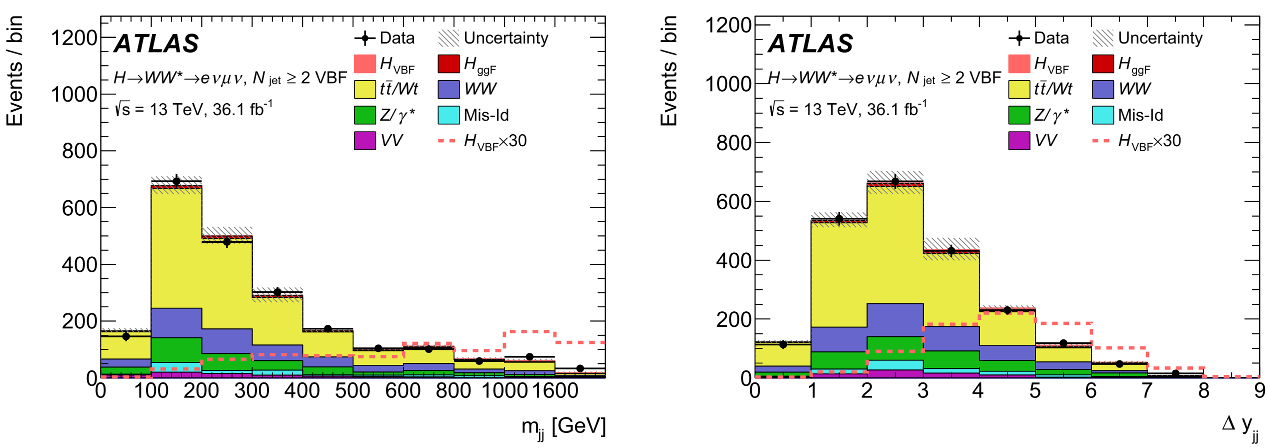
Fig. 2. Jet multiplicity distribution after applying the preselection criteria. The shaded band represents the systematic uncertainty and accounts for experimental uncertainties only.

Events are classified into one of three categories based on the number of jets with $p_{\mathrm{T}} > 30$ GeV: events with zero jets and events with exactly one jet target the ggF production mode ($N_{\mathrm{jet}} = 0$ and $N_{\mathrm{jet}} = 1$ ggF categories), and events with at least two jets target the VBF production mode ($N_{\mathrm{jet}} \geq 2$ VBF category). Fig. 2 shows the jet multiplicity distribution after applying the preselection criteria defined in Table 2. The different background compositions as a function of jet multiplicity motivate the division of the data sample into the various N_{jet} categories and the definition of a signal region in each jet multiplicity bin. Details of the background estimation are provided in Section 5. To reject background from top-quark production, events containing b-jets with $p_{\mathrm{T}} > 20$ GeV ($N_{b\text{-jet},(p_{\mathrm{T}}>20\ \mathrm{GeV})}$) are vetoed. The full event selection is summarised in Table 2, where $\Delta\phi(\ell\ell, E_{\mathrm{T}}^{\mathrm{miss}})$ is defined as the azimuthal angle between $\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}$ and the dilepton system, $p_{\mathrm{T}}^{\ell\ell}$ is the transverse momentum of the dilepton system, $m_{\ell\ell}$ is



(a) (b)

Fig. 3. Post-fit m_T distributions with the signal and the background modelled contributions in the (a) $N_{jet} = 0$ and (b) $N_{jet} = 1$ signal regions. The hatched band shows the total uncertainty of the signal and background modelled contributions.



(a) (b)

Fig. 4. Post-fit m_{jj} (a) and Δy_{jj} (b) distributions with signal and background modelled contributions in the $N_{jet} \geq 2$ VBF signal region. The dashed line shows the VBF signal scaled by a factor of 30. The hatched band shows the total uncertainty of the signal and background modelled contributions.

Table 3
Event selection criteria used to define the control regions. Every control region selection starts from the selection labelled "Preselection" in Table 2. $N_{b\text{-jet},(20\text{ GeV}<p_T<30\text{ GeV})}$ represents the number of b-jets with 20 GeV $< p_T <$ 30 GeV.

<table>
<tr><th>CR</th><th>$N_{\text{jet},(p_T>30\text{ GeV})} = 0$ ggF</th><th>$N_{\text{jet},(p_T>30\text{ GeV})} = 1$ ggF</th><th>$N_{\text{jet},(p_T>30\text{ GeV})} \geq 2$ VBF</th></tr>
<tr><td rowspan="3">WW</td><td>$55 < m_{\ell\ell} < 110$ GeV
$\Delta\phi_{\ell\ell} < 2.6$</td><td>$m_{\ell\ell} > 80$ GeV
$|m_{\tau\tau} - m_Z| > 25$ GeV</td><td rowspan="3"></td></tr>
<tr><td colspan="2">$N_{b\text{-jet},(p_T>20\text{ GeV})} = 0$</td></tr>
<tr><td></td><td>$\max\left(m_T^{\ell}\right) > 50$ GeV</td></tr>
<tr><td rowspan="3">$t\bar{t}/Wt$</td><td rowspan="3">$N_{b\text{-jet},(20\text{ GeV}<p_T<30\text{ GeV})} > 0$
$\Delta\phi(\ell\ell, E_T^{miss}) > \pi/2$
$p_T^{\ell\ell} > 30$ GeV
$\Delta\phi_{\ell\ell} < 2.8$</td><td>$N_{b\text{-jet},(p_T>30\text{ GeV})} = 1$
$N_{b\text{-jet},(20\text{ GeV}<p_T<30\text{ GeV})} = 0$
$\max\left(m_T^{\ell}\right) > 50$ GeV</td><td>$N_{b\text{-jet},(p_T>20\text{ GeV})} = 1$
central jet veto</td></tr>
<tr><td colspan="2">$m_{\tau\tau} < m_Z - 25$ GeV</td></tr>
<tr><td></td><td>outside lepton veto</td></tr>
<tr><td rowspan="3">Z/γ^*</td><td colspan="3">$N_{b\text{-jet},(p_T>20\text{ GeV})} = 0$
$m_{\ell\ell} < 80$ GeV</td></tr>
<tr><td colspan="2">no p_T^{miss} requirement</td><td rowspan="2">central jet veto
outside lepton veto
$|m_{\tau\tau} - m_Z| \leq 25$ GeV</td></tr>
<tr><td>$\Delta\phi_{\ell\ell} > 2.8$</td><td>$\max\left(m_T^{\ell}\right) > 50$ GeV
$m_{\tau\tau} > m_Z - 25$ GeV</td></tr>
</table>

the invariant mass of the two leptons, $\Delta\phi_{\ell\ell}$ is the azimuthal angle between the two leptons, and $\max\left(m_{\mathrm{T}}^{\ell}\right)$ is the larger of $m_{\mathrm{T}}^{\ell_i} = \sqrt{2\, p_{\mathrm{T}}^{\ell_i} \cdot E_{\mathrm{T}}^{\mathrm{miss}} \cdot \left(1 - \cos\Delta\phi\left(\ell_i, E_{\mathrm{T}}^{\mathrm{miss}}\right)\right)}$, where ℓ_i can be either the leading or the subleading lepton. The "outside lepton veto" requires the two leptons to reside within the rapidity gap spanned by the two leading jets, and the "central jet veto" rejects events with additional jets with $p_{\mathrm{T}} > 20$ GeV in the rapidity gap between the two leading jets. In the $N_{\mathrm{jet}} = 1$ and $N_{\mathrm{jet}} \geq 2$ categories, the invariant mass of the τ-lepton pair ($m_{\tau\tau}$), calculated using the collinear approximation [71], is used to veto background from $Z \to \tau\tau$ production. Signal regions (SRs) are defined in each N_{jet} category after applying all selection criteria. For both the $N_{\mathrm{jet}} = 0$ and $N_{\mathrm{jet}} = 1$ ggF SRs, eight regions, later used for the fit, are defined by subdividing in $m_{\ell\ell}$ at $m_{\ell\ell} < 30$ GeV and $m_{\ell\ell} \geq 30$ GeV, in p_{T} of the subleading lepton at $p_{\mathrm{T}}^{\mathrm{sublead}} < 20$ GeV and $p_{\mathrm{T}}^{\mathrm{sublead}} \geq 20$ GeV, and by the flavour of the subleading lepton. For the categories with zero jets and with exactly one jet, the discriminating variable between signal and SM background processes is the dilepton transverse mass, defined as $m_{\mathrm{T}} = \sqrt{\left(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}}\right)^2 - \left|\mathbf{p}_{\mathrm{T}}^{\ell\ell} + \boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}\right|^2}$ where $E_{\mathrm{T}}^{\ell\ell} = \sqrt{|\mathbf{p}_{\mathrm{T}}^{\ell\ell}|^2 + m_{\ell\ell}^2}$ and $\mathbf{p}_{\mathrm{T}}^{\ell\ell}$ is the vector sum of the lepton transverse momenta. The discriminating variable m_{T} is used in the ggF SRs, with eight bins for the $N_{\mathrm{jet}} = 0$ and six bins for the $N_{\mathrm{jet}} = 1$ regions. The bin boundaries are chosen such that approximately the same number of signal events is expected in each bin. The m_{T} distributions for the $N_{\mathrm{jet}} = 0$ and $N_{\mathrm{jet}} = 1$ SRs are shown in Fig. 3. All figures in this Letter, except Fig. 2, use signal and background normalisations as fitted by the final statistical analysis of all signal and control regions, including pulls of statistical and systematic uncertainty parameters (post-fit). For the $N_{\mathrm{jet}} \geq 2$ VBF selection, a boosted decision tree (BDT) [72] is used to enhance discrimination power between the VBF signal and backgrounds, including the ggF process. Kinematic variables of the two leading jets (j) and the two leading leptons (ℓ) are used as inputs to the BDT: the invariant masses (m_{jj}, $m_{\ell\ell}$), the difference between the two jet rapidities (Δy_{jj}), and the difference between the azimuthal angles of the two leptons ($\Delta\phi_{\ell\ell}$). Other variables used in the BDT training are: m_{T}, the lepton η-centrality ($\sum_\ell C_\ell$, where $C_\ell = |2\eta_\ell - \sum \eta_j| / \Delta\eta_{jj}$), which quantifies the positions of the leptons relative to the leading jets in pseudorapidity [73], the sum of the invariant masses of all four possible lepton–jet pairs ($\sum_{\ell,j} m_{\ell j}$), and the total transverse momentum ($p_{\mathrm{T}}^{\mathrm{tot}}$), which is defined as the magnitude of the vectorial sum of all selected objects. The observables providing the best discrimination between signal and background are m_{jj} and Δy_{jj}, and are shown in Fig. 4 after applying all selections. The BDT score reflects the compatibility of an event with VBF-like kinematics. Signal-like events would tend to have high BDT score, while background-like events tend to have low BDT score. The signal purity, therefore, increases at high values of BDT score. The BDT score is used as the discriminating variable in the statistical analysis with four bins. The bin boundaries are chosen to maximise the expected sensitivity for the VBF production mode, resulting in smaller bin widths for larger values of the BDT score. In the highest-score BDT bin, the expected signal-to-background ratio of the VBF signal is approximately 0.6. The BDT distribution for the VBF-enriched region is presented in Fig. 5.

5. Background estimation

The background contamination in the SRs originates from various processes: non-resonant WW, top-quark pair ($t\bar{t}$) and single-top-quark (Wt), diboson (WZ, ZZ, $W\gamma$ and $W\gamma^*$) and Drell–Yan (mainly $Z \to \tau\tau$, hereafter denoted Z/γ^*) production. Other background contributions arise from W +jets and multi-jet production with misidentified leptons, which are either non-prompt leptons from decays of heavy-flavour hadrons or jets faking prompt leptons. Dedicated regions in data, identified hereafter as control regions (CRs), are used to normalise the predictions of some of the background processes. CRs are defined for the main background processes: WW (only for $N_{\mathrm{jet}} \leq 1$ final states), $t\bar{t}/Wt$, and Z/γ^*. Table 3 summarises the event selection for all CRs. For the $N_{\mathrm{jet}} = 0$ and $N_{\mathrm{jet}} = 1$ WW CRs, $m_{\ell\ell}$ selections orthogonal to those of the SRs are applied. For the $t\bar{t}/Wt$ CRs, the b-veto is replaced with a b-tag requirement. For the $N_{\mathrm{jet}} = 1$ and $N_{\mathrm{jet}} \geq 2$ VBF Z/γ^* CRs, the $m_{\tau\tau}$ selection is inverted, while for the $N_{\mathrm{jet}} = 0$ Z/γ^* CR the $\Delta\phi_{\ell\ell}$ selection criterion is inverted. Fig. 6 presents the post-fit m_{T} distributions in the $N_{\mathrm{jet}} = 0$ and $N_{\mathrm{jet}} = 1$ CRs.

In Fig. 7, the post-fit Δy_{jj} distributions in the $N_{\mathrm{jet}} \geq 2$ VBF CRs are shown. Data and simulation are in agreement within uncertainties for all the relevant distributions in the different CRs. The background contributions with misidentified leptons are estimated using a data-driven technique. A control sample where one of the two lepton candidates fails to meet the nominal identification and isolation criteria but satisfies looser identification criteria, referred as an anti-identified lepton, is used. The contribution of this background in the SRs and CRs is then obtained by scaling the number of data events, after the subtraction of processes with two prompt leptons, in the control samples by an extrapolation factor. The latter is measured in a Z+jets-enriched data sample, where the Z boson decays to a pair of electrons or muons, and the misidentified lepton candidate recoils against the Z boson. The extrapolation factor is defined as the ratio of the numbers of identified and anti-identified leptons, and is measured in bins of p_{T} and η. Furthermore, a sample composition correction factor is applied separately in $p_{\mathrm{T}} < 25$ GeV and $p_{\mathrm{T}} > 25$ GeV bins, and is defined in each bin as the ratio of the extrapolation factors measured in W+jets and Z+jets MC simulation. The total uncertainty of the background with misidentified leptons includes uncertainties due to the difference in sample composition between the

Table 4
Post-fit normalisation factors which scale the corresponding estimated yields in the signal region; the dash indicates where MC-based normalisation is used. The errors include the statistical and systematic uncertainties.

Category	WW	$t\bar{t}/Wt$	Z/γ^*
$N_{\mathrm{jet},(p_{\mathrm{T}}>30\ \mathrm{GeV})} = 0$ ggF	1.06 ± 0.09	0.99 ± 0.17	0.84 ± 0.04
$N_{\mathrm{jet},(p_{\mathrm{T}}>30\ \mathrm{GeV})} = 1$ ggF	0.97 ± 0.17	0.98 ± 0.08	0.90 ± 0.12
$N_{\mathrm{jet},(p_{\mathrm{T}}>30\ \mathrm{GeV})} \geq 2$ VBF	–	1.01 ± 0.01	0.93 ± 0.07

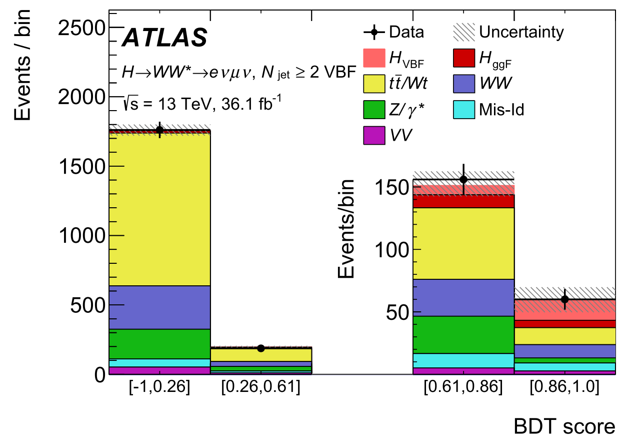


Fig. 5. Post-fit BDT score distribution with the signal and the background modelled contributions in the VBF signal region. The hatched band shows the total uncertainty of the signal and background modelled contributions.

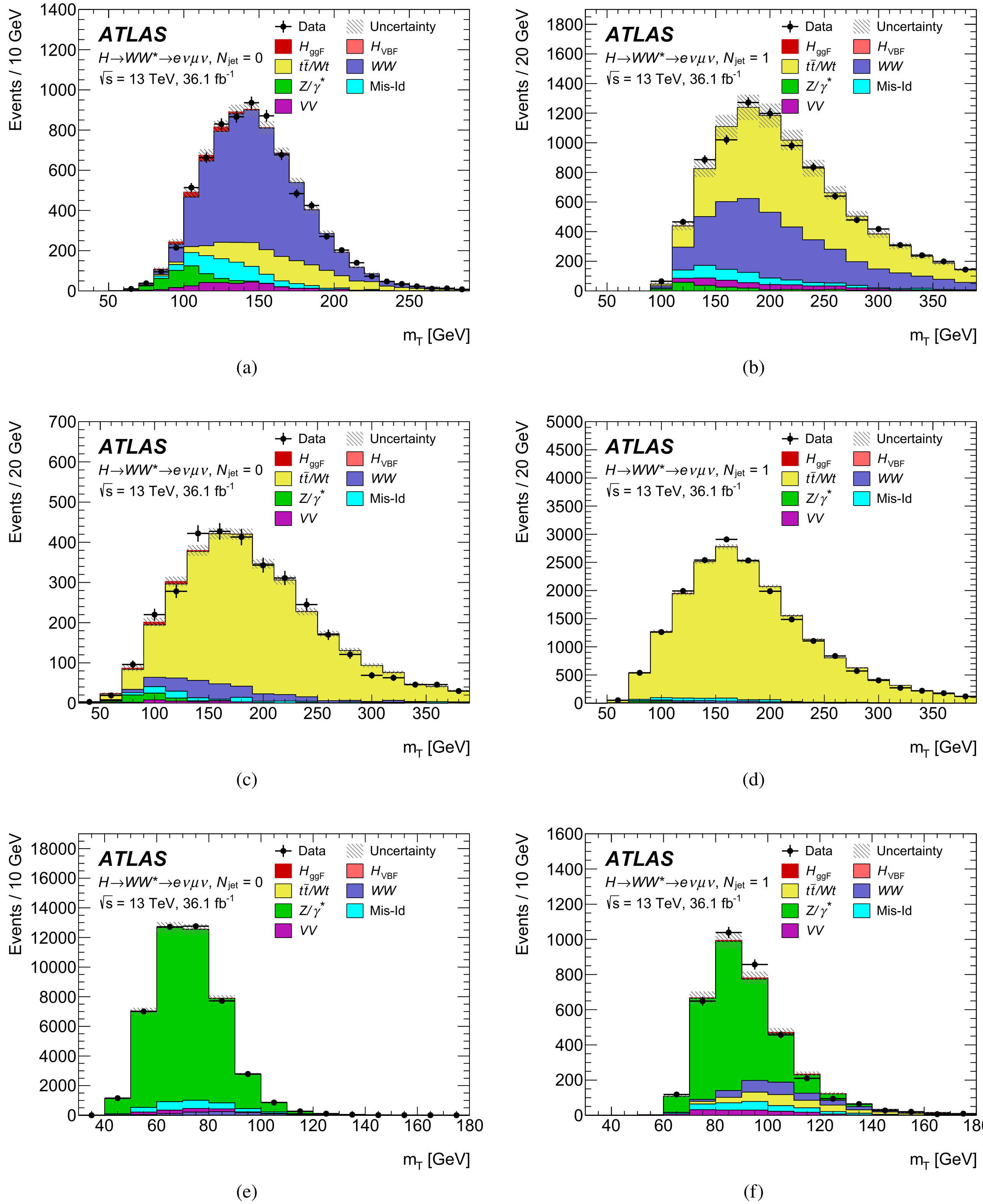
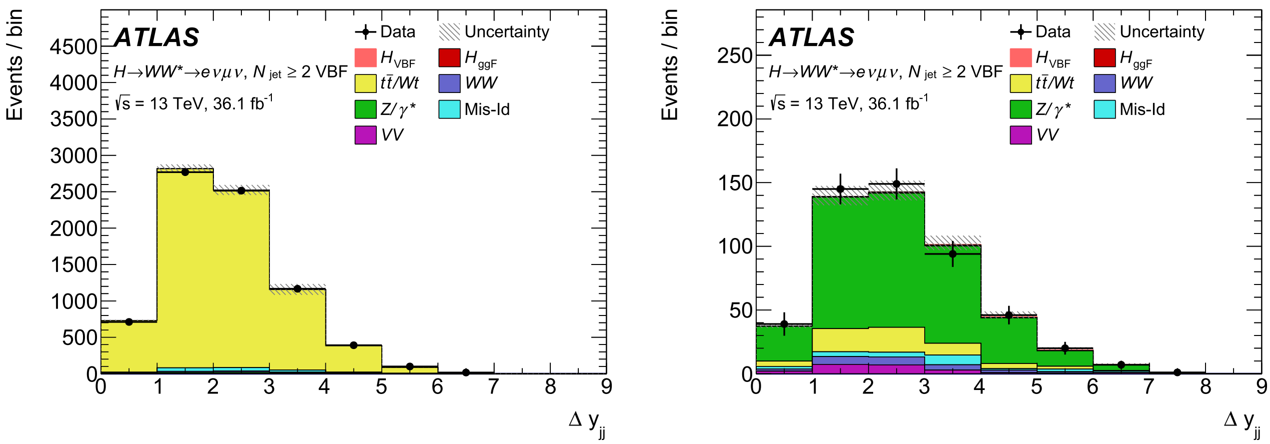


Fig. 6. Post-fit m_T distributions with signal and background modelled contributions in the $N_{jet} = 0$ and $N_{jet} = 1$ control regions for the WW (a, b), $t\bar{t}/Wt$ (c, d), and Z/γ^* (e, f) processes. The hatched band shows the total uncertainty of the signal and background modelled contributions. Some contributions are too small to be visible.



(a) (b)

Fig. 7. Post-fit Δy_{jj} distribution with signal and background modelled contributions in the (a) $t\bar{t}/Wt$ and (b) Z/γ^* control regions in the $N_{\text{jet}} \geq 2$ VBF analysis category. The hatched band shows the total uncertainty of the signal and background modelled contributions. Some contributions are too small to be visible.

W+jets and Z+jets control samples determined with MC simulation, the statistical uncertainty of the Z+jets control sample, and the subtraction of other processes. In the VBF regions, the background estimation is corrected for the contamination from events with two misidentified leptons, whose origin is largely multi-jet events. This contribution is negligible in other regions. Details of this method can be found in Ref. [1].

The post-fit background normalisation factors are summarised in Table 4. The Z/γ^* normalisation factors are affected by residual misalignments in the inner detector which distort the measurements of the track parameters for particles originating from secondary vertices e.g. leptons from τ decays.

6. Systematic uncertainties

The sources of uncertainty can be classified into two categories: experimental and theoretical. The dominant experimental uncertainties are the jet energy scale and resolution [74], and the b-tagging efficiency [75]. Other sources of uncertainty are lepton energy (momentum) scale and resolution, identification and isolation [63,64,76], missing transverse momentum measurement [77], modelling of pile-up, and luminosity measurement [78]. The luminosity uncertainty is only applied to the Higgs boson signal and to background processes that are normalised to theoretical predictions. For the main processes, the theoretical uncertainties are assessed by a comparison between nominal and alternative event generators and UEPS models, as indicated in Table 1. For the prediction of WZ, ZZ, $V\gamma^*$, and $V\gamma$ production (VV), variations of the matching scale are considered instead of an alternative generator. In addition, the effects of QCD factorisation and renormalisation scale variations and PDF model uncertainties are evaluated.

7. Signal region yields and results

The ggF and VBF cross-sections are obtained from a simultaneous statistical analysis of the data samples in all SRs and CRs by maximising a likelihood function in a fit using scaling parameters multiplying the predicted total production cross-section of each signal process and applying the profile likelihood method. The CRs are used to determine the normalisation of the corresponding backgrounds. The systematic uncertainties enter the fit as nuisance parameters in the likelihood function.

Table 5 shows the post-fit yields for all of the three SRs. Yields in the highest-score VBF BDT bin are also given. The uncertainties in the total yields are smaller than those of some of the individual background processes. This effect is due to correlations among different data regions, background processes, and nuisance parameters. The correlations are imposed by the fit as it constrains the total yield to match the data. For example, for the b-tagging efficiency, which is the main source of uncertainty in the $t\bar{t}/Wt$ yields in the SRs as well as in WW CRs, the combination of these two regions in the statistical analysis leads to an anti-correlation between the SR yields of the WW and $t\bar{t}/Wt$ backgrounds. Changes in the b-tagging efficiency simultaneously increase/decrease the yields of $t\bar{t}/Wt$ and WW backgrounds, resulting in a small uncertainty in the combined yields of the processes but large uncertainties in the individual components.

Table 5
Post-fit MC and data yields in the ggF and VBF SRs. Yields in the highest-score VBF BDT bin are also presented. The quoted uncertainties include the theoretical and experimental systematic sources and those due to sample statistics. The sum of all the contributions may differ from the total value due to rounding. Moreover, the total uncertainty differs from the sum in quadrature of the single-process uncertainties due to the correlations.

Process	$N_{\text{jet}}=0$ ggF	$N_{\text{jet}}=1$ ggF	$N_{\text{jet}} \geq 2$ VBF	
			Inclusive	BDT: [0.86, 1.0]
H_{ggF}	639 ± 110	285 ± 51	42 ± 16	6 ± 3
H_{VBF}	7 ± 1	31 ± 2	28 ± 16	16 ± 6
WW	3016 ± 203	1053 ± 206	400 ± 60	11 ± 2
VV	333 ± 38	208 ± 32	70 ± 12	3 ± 1
$t\bar{t}/Wt$	588 ± 130	1397 ± 179	1270 ± 80	14 ± 2
Mis-Id	447 ± 77	234 ± 49	90 ± 30	6 ± 2
Z/γ^*	27 ± 11	76 ± 24	280 ± 40	4 ± 1
Total	5067 ± 80	3296 ± 61	2170 ± 50	60 ± 10
Observed	5089	3264	2164	60

Fig. 8 shows the combined m_{T} distribution for $N_{\text{jet}} \leq 1$. The bottom panel of Fig. 8 shows the difference between the data and the total estimated background compared to the m_{T} distribution of a SM Higgs boson with $m_H = 125$ GeV. The total signal observed (see Table 5) of about 1000 events is in agreement, in both shape and rate, with the expected SM signal. The cross-section times branching fractions, $\sigma_{\text{ggF}} \cdot \mathcal{B}_{H\to WW^*}$ and $\sigma_{\text{VBF}} \cdot \mathcal{B}_{H\to WW^*}$, are simultaneously determined to be:

$$\begin{aligned}
&\sigma_{\text{ggF}} \cdot \mathcal{B}_{H\to WW^*} \\
&\quad = 11.4^{+1.2}_{-1.1}(\text{stat.})^{+1.2}_{-1.1}(\text{theo syst.})^{+1.4}_{-1.3}(\text{exp syst.})\ \text{pb} \\
&\quad = 11.4^{+2.2}_{-2.1}\ \text{pb}
\end{aligned}$$

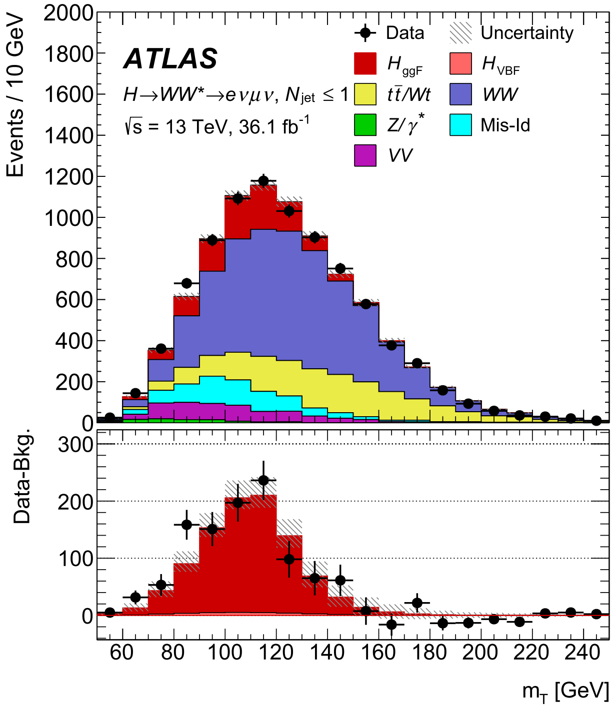


Fig. 8. Post-fit combined transverse mass distribution for $N_{\text{jet}} \leq 1$. The bottom panel shows the difference between the data and the estimated background compared to the distribution for a SM Higgs boson with $m_H = 125$ GeV. The signal and the background modelled contributions are fitted to the data with a floating signal strength. The hatched band shows the total uncertainty of the signal and background modelled contributions. The H_{VBF} contribution is too small to be visible.

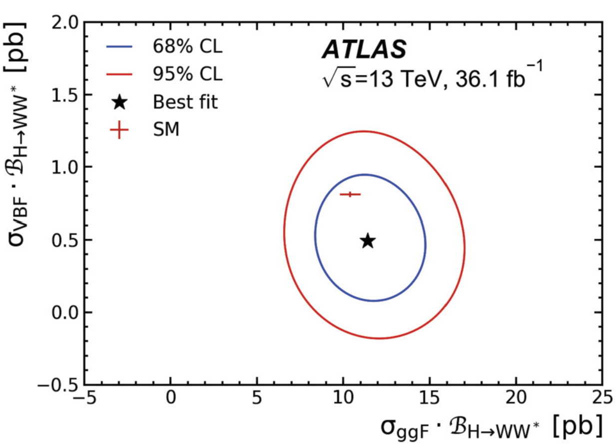


Fig. 9. 68% and 95% confidence level two-dimensional likelihood contours of $\sigma_{\text{ggF}} \cdot \mathcal{B}_{H\rightarrow WW^*}$ vs. $\sigma_{\text{VBF}} \cdot \mathcal{B}_{H\rightarrow WW^*}$, compared to the SM prediction shown by the red marker. The error bars on the SM prediction represent the ggF and VBF theory uncertainty [23], respectively.

$$\sigma_{\text{VBF}} \cdot \mathcal{B}_{H\rightarrow WW^*}$$
$$= 0.50^{+0.24}_{-0.22}(\text{stat.}) \pm 0.10(\text{theo syst.})^{+0.12}_{-0.13}(\text{exp syst.}) \text{ pb}$$
$$= 0.50^{+0.29}_{-0.28} \text{ pb}.$$

The predicted cross-section times branching fraction values are 10.4 ± 0.6 pb and 0.81 ± 0.02 pb for ggF and VBF [23], respectively. The 68% and 95% confidence level two-dimensional contours of $\sigma_{\text{ggF}} \cdot \mathcal{B}_{H\rightarrow WW^*}$ and $\sigma_{\text{VBF}} \cdot \mathcal{B}_{H\rightarrow WW^*}$ are shown in Fig. 9 and are consistent with the SM predictions.

The signal strength parameter μ is defined as the ratio of the measured signal yield to that predicted by the SM. The measured signal strengths for the ggF and VBF production modes in the $H \rightarrow WW^*$ decay channel are simultaneously determined to be

$$\mu_{\text{ggF}} = 1.10^{+0.10}_{-0.09}(\text{stat.})^{+0.13}_{-0.11}(\text{theo syst.})^{+0.14}_{-0.13}(\text{exp syst.})$$
$$= 1.10^{+0.21}_{-0.20}$$
$$\mu_{\text{VBF}} = 0.62^{+0.29}_{-0.27}(\text{stat.})^{+0.12}_{-0.13}(\text{theo syst.}) \pm 0.15(\text{exp syst.})$$
$$= 0.62^{+0.36}_{-0.35}.$$

Table 6
Breakdown of the main contributions to the total uncertainty in $\sigma_{\text{ggF}} \cdot \mathcal{B}_{H\rightarrow WW^*}$ and $\sigma_{\text{VBF}} \cdot \mathcal{B}_{H\rightarrow WW^*}$. The individual sources of systematic uncertainties are grouped together. The sum in quadrature of the individual components differs from the total uncertainty due to correlations between the components.

Source	$\Delta\sigma_{\text{ggF}} \cdot \mathcal{B}_{H\rightarrow WW^*}$ [%]	$\Delta\sigma_{\text{VBF}} \cdot \mathcal{B}_{H\rightarrow WW^*}$ [%]
Data statistics	10	46
CR statistics	7	9
MC statistics	6	21
Theoretical uncertainties	10	19
ggF signal	5	13
VBF signal	<1	4
WW	6	12
Top-quark	5	5
Experimental uncertainties	8	9
b-tagging	4	6
Modelling of pile-up	5	2
Jet	2	2
Lepton	3	<1
Misidentified leptons	6	9
Luminosity	3	3
TOTAL	18	57

Table 6 shows the relative impact of the main uncertainties on the measured values for $\sigma_{\text{ggF}} \cdot \mathcal{B}_{H\rightarrow WW^*}$ and $\sigma_{\text{VBF}} \cdot \mathcal{B}_{H\rightarrow WW^*}$. The theory uncertainties in the non-resonant WW background produce one of the largest uncertainties, of the order of 6%, in the measured ggF cross-section. The uncertainty in the ratio of $gg \rightarrow WW$ to $qq \rightarrow WW$ comes from the limited NLO accuracy of the $gg \rightarrow WW$ production cross-section [38]. The resulting uncertainty in the cross-section when using acceptance criteria similar to those in this analysis was evaluated in Ref. [79] for $N_{\text{jet}} = 0$ and for $N_{\text{jet}} = 1$. In the $N_{\text{jet}} \geq 2$ VBF SR, the 12% uncertainty in the WW background originates from the matching and UEPS modelling of $qq \rightarrow WW$. The amount of ggF contamination in the VBF region is subject to QCD scale uncertainties and this produces an uncertainty of about 13% in the measured VBF cross-section. The statistical uncertainty of the MC simulation has a relatively large impact, especially for the VBF cross-section measurement, where it contributes 21%.

The observed (expected) ggF and VBF signals have significances of 6.0 (5.3) and 1.8 (2.6) standard deviations, respectively.

8. Conclusions

Measurements of the inclusive cross-section of Higgs boson production via the gluon–gluon fusion (ggF) and vector-boson fusion (VBF) modes in the $H \rightarrow WW^*$ decay channel are presented. They are based on 36.1 fb^{-1} of $\sqrt{s} = 13$ TeV proton–proton collisions recorded by the ATLAS detector at the LHC in 2015–2016. The ggF and VBF cross-sections times the $H \rightarrow WW^*$ branching ratio are measured to be $11.4^{+1.2}_{-1.1}(\text{stat.})^{+1.8}_{-1.7}(\text{syst.})$ pb and $0.50^{+0.24}_{-0.22}(\text{stat.}) \pm 0.17(\text{syst.})$ pb, respectively, in agreement with SM prediction.

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